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Ignacio Díaz-Martínez, Silvina de Valais & Carlos Cónsole-Gonella

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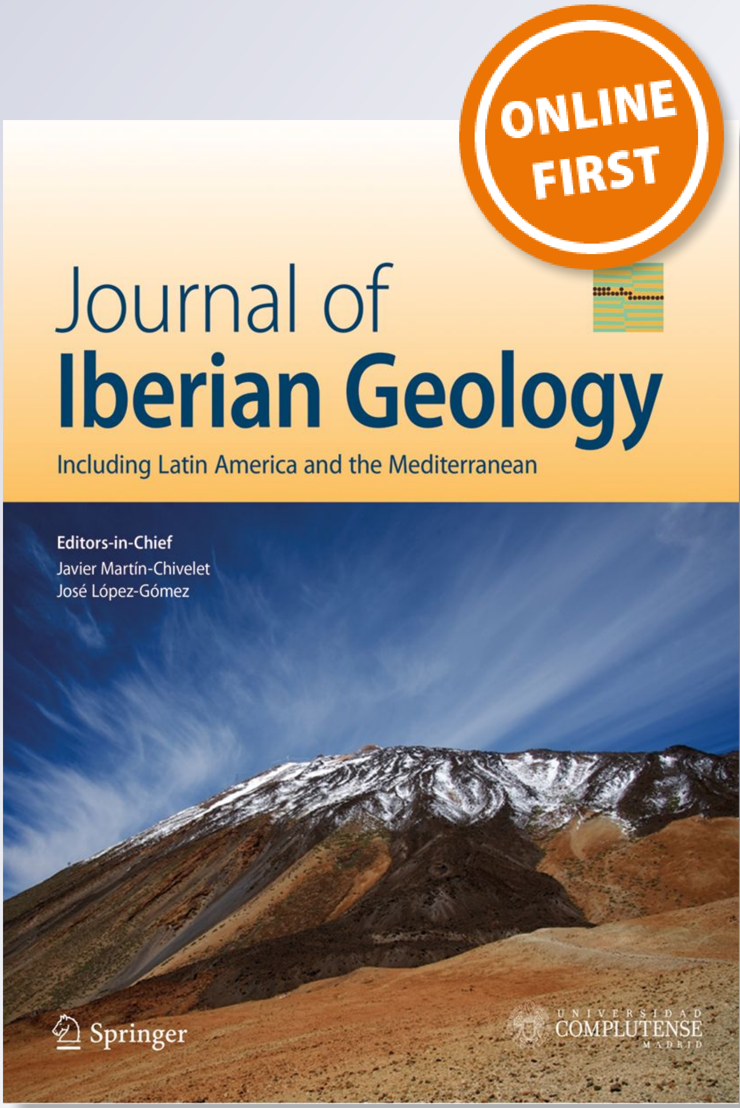

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RESEARCH ARTICLE

New sauropod tracks from the Yacoraite Formation (Maastrichtian–Danian), Valle del Tonco tracksite, Salta, northwestern Argentina

Ignacio Díaz-Martínez[1,2] · **Silvina de Valais**[1,2] · **Carlos Cónsole-Gonella**[1,3]

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Abstract
Purpose A relative long sauropod trackway and hundreds of varied indeterminate dinosaur tracks, many of them probably related to ornitischians, were found many years ago in the Valle del Tonco tracksite (Salta, northwestern Argentina). This sauropod trackway is now described and analyzed in an updated context.
Methods Ichnological analyses were mainly conducted during fieldwork. Fossiliferous surface was mapped and digitalized in order to recognize the track shape and their distribution.
Results The trackway-bearing surface belongs to an inverted section from the uppermost Cretaceous Caliza Amblayo Member, the lower unit of the Yacoraite Formation in this area. The sauropod trackway is moderate to poorly-preserved and includes twelve manus–pes imprint sets as convex hyporelief (natural casts). The heteropody is high and the PTR index indicates a medium category for the trackway gauge. The pes tracks, longer than wide, have subtriangular posterior edge and a general rhomboidal shape, lacking a lateral notch, and the digit-claw traces are laterally located. The manus tracks are subrounded to rectangular with at least two short, posteriorly oriented digit imprints.
Conclusions Their main features and preservation/weathering do not allow a precise assignment to a particular ichnotaxon. Taking into account the best-preserved Campanian–Maastrichtian sauropod pes tracks, two different general shapes can be differentiated: the Campanian Humaca shape (Bolivia) and the Maastrichtian Fumanya shape (Spain). The Valle del Tonco pes prints show similarities with the Fumanya shape. The presence of two pes track shapes in this age suggests that at least two different titanosaur feet morphology were present in the uppermost Cretaceous.

Keywords Sauropod trackway · Caliza Amblayo Member · Uppermost Cretaceous · South America

Resumen
Objetivo Varios años atrás se ha encontrado una rastrillada saurópoda relativamente larga y cientos de huellas indeterminadas de dinosaurio, muchas de ellas probablemente relacionadas con ornitisquios, en el sitio icnológico Valle del Tonco (Salta, noroeste argentino). En este trabajo, se describe y analiza en un contexto actualizado esta rastrillada saurópoda.
Métodos Los análisis icnológicos fueron pricipalmente desarrollados durante el trabajo de campo. La superficie fosilífera fue mapeada y digitalizada para reconocer la forma de las huellas y su distribución.
Resultados La superficie portadora de las huellas pertenece a una sección invertida de la unidad inferior de la Formación Yacoraite en el área, el Miembro Caliza

✉ Ignacio Díaz-Martínez
inaportu@hotmail.com

Silvina de Valais
sdevalais@yahoo.com.ar

Carlos Cónsole-Gonella
carlosconsole@csnat.unt.edu.ar

1 Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Buenos Aires, Argentina

2 Instituto de Investigación en Paleobiología y Geología (IIPG), Universidad Nacional de Río Negro, Av. Roca 1242, 8332 General Roca, Río Negro, Argentina

3 Instituto Superior de Correlación Geológica (INSUGEO), Universidad Nacional de Tucumán-CONICET, Miguel Lillo 205, 4000 Tucumán, Argentina

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Amblayo del Cretácico Superior. La rastrillada saurópoda está entre moderada a mal conservada e incluye doce pares mano-pie como hiporrelieve convexos (contramoldes). La heteropodía es alta y el índice PTR indica una rastrillada de vía intermedia. Las huellas de los pies son más largas que anchas, y tienen el borde posterior subtriangular, una forma general romboidal, carecen de una escotadura lateral, y las impresiones de las uñas se localizan lateralmente. Las huellas de las manos son subredondeadas a rectangulares con al menos dos impresiones de dedos cortos orientados posteriormente.

Conclusiones Debido a las características principales y al estado de conservación/meterorización de estas huellas no es posible hacer una asignación precisa a un icnotaxón en particular. Se pueden diferenciar dos formas de huellas de pie de saurópodo del Campaniense-Maastrichtiense teniendo en cuenta sólo huellas bien conservadas: la forma campaniense de Humaca (Bolivia), y la forma maastrichtiense de Fumanya (España). Las huellas de pie de Valle del Tonco muestran similitudes con la forma de Fumanya. La presencia de dos formas diferentes de improntas de pie saurópodas en esa edad sugiere que en el Cretácico final al menos hubo dos tipos de pie entre los titanosaurios.

Palabras clave Rastrillada saurópoda · Miembro Caliza Amblayo · Cretácico final · Sur América

1 Introduction

One of the reasons because the Yacoraite Formation is a well-known geological unit is its vertebrate ichnological record. Raskovsky (1968) described the first records from the Valle del Tonco tracksite (Salta province) in an unpublished report from the CNEA (Comisión Nacional de Energía Atómica, spanish for Atomic Energy National Commission). Lately, the first ichnotaxonomic approaches were made, and as result, several ichnospecies were defined, originally assigned to theropods (*Salfitichnus mentoor* Alonso and Marquillas, 1986), hadrosaurids (*Taponichnus donottoi* Alonso and Marquillas, 1986 and *Hadrosaurichnus australis* Alonso, 1980), ornithopods (*Telosichnus saltensis* Alonso and Marquillas, 1986), and even avian trackmakers (*Yacoraitichnus avis* Alonso and Marquillas, 1986) (for other ichnotaxonomic proposals see Lockley et al. 2014; Díaz-Martínez et al. 2015; Cónsole-Gonella et al. 2017; de Valais and Cónsole-Gonella 2017, submitted).

Although sauropod tracks are abundant in correlative units from the Late Cretaceous of the Central Andes basin (e.g., Leonardi 1984; Meyer et al. 2001; Lockley et al. 2002), the report of such kind of tracks from the Yacoraite Formation is recent. Cónsole-Gonella et al. (2012, 2013, 2017) mentioned and analyzed sauropod tracks from the northern sub-basin of the Yacoraite basin (Tres Cruces sub-basin), in the Jujuy province (Fig. 1). Despite the high degree of trampling and consequent impossibility of measuring trackway parameters, it appears that the trackways are moderately wide-gauge (Cónsole-Gonella et al. 2017).

A relative long trackway, assigned to a large quadrupedal vertebrate, have been found in the Valle del Tonco tracksite many years ago by the CNEA geologists, from the Quebrada de El Candado locality. Recently, these tracks have been referred as a sauropod trackway by Cónsole-Gonella et al. (2015) and de Valais et al. (2016).

The aims of this contribution are (1) to describe in detail the sauropod trackway, (2) to study and discuss the ichnotaxonomy of this trackway, and finally (3) to compare it with similar sauropod tracks from the Campanian–Maastrichtian time lapse.

2 Geological setting

2.1 Geology and regional context

The Yacoraite Formation is the middle unit of the Balbuena Subgroup (Late Campanian?—Selandian?), which is the early post-rift stage of the Salta Group (Hauterivian?—Oligocene) basin (Marquillas et al. 2005). This rift system is part of the extensional context of the Late Cretaceous Andean basin that records the epeiric marine incursion in most of South America (e.g., Riccardi 1988; Salfity and Zambrano 1990). This process generated several correlative basins along the Central Andes (see Marquillas et al. 2011), with dominance of carbonate–siliciclastic systems. The filling of the basin took place in several sub-basins (Reyes 1972; Salfity 1982), and the record presented here belongs to the Alemanía sub-basin (Fig. 1).

The Yacoraite Formation is composed mainly of grey carbonates with varied depositional textures that are largely dolomitic; in some of the proximal sections, calcareous sandstones and pelites are the major component (Marquillas et al. 2005). Regarding the age of the unit, the Yacoraite Formation is recognized as Maastrichtian–Danian (Marquillas 1985), so the Cretaceous–Paleogene boundary occurred during its accumulation. U–Pb dating in the Metán sub-basin (Salta province) is indicative of a Late Maastrichtian age (Marquillas et al. 2011). However, dated strata are located several meters below the top of the unit (Marquillas et al. 2011). The formation contains dinosaur tracks (e.g., Alonso and Marquillas 1986), some tracks even restricted to the uppermost Cretaceous (Díaz-Martínez et al. 2016), and Maastrichtian and Danian palynomorphs (Moroni 1984). The overall palaeontological

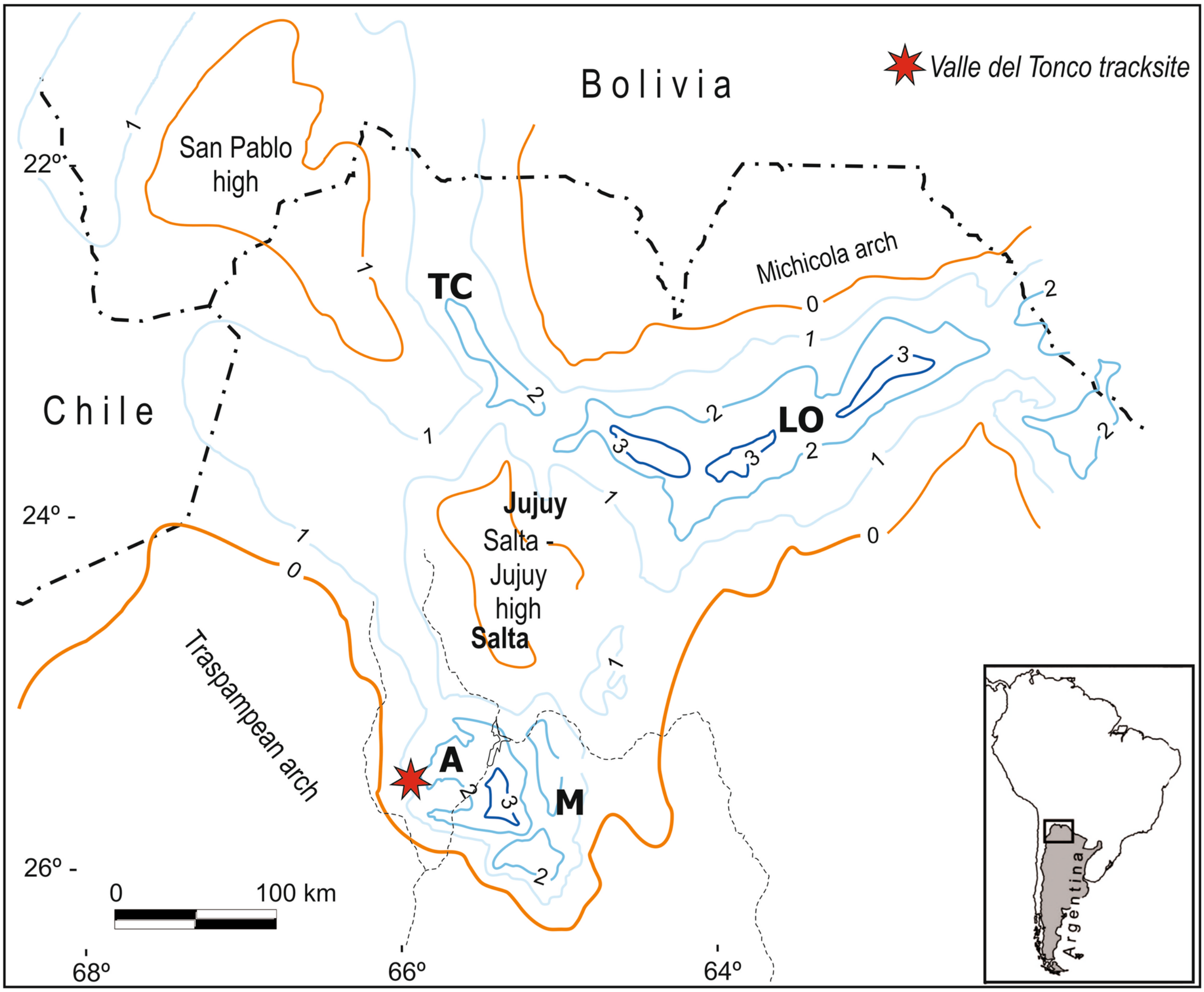


Fig. 1 Isopach map of the Yacoraite Formation. Main sub-basins: *TC* Tres Cruces, *LO* Lomas de Olmedo, *A* Alemanía, *M* Metán. Thickness in hundreds of meters. After Marquillas et al. (2005)

record is abundant but lacking in diversity, according to the interpretation of the unit as part of an epeiric restricted sea (Marquillas et al. 2005, and references therein).

2.2 Stratigraphy

At the southern section of the Valle del Tonco area, in the Alemanía sub-basin (Figs. 1, 2), the Yacoraite Formation is placed in disconformity over an Ediacaran–Lower Cambrian basement, which is part of the Puncoviscana Formation *s.l.* (Gorustovich et al. 2013). In this context, the Yacoraite Formation exhibits three members from bottom to the top, in increasing order (Raskovsky 1970): (1) Caliza Amblayo, (2) Complejo Don Otto, and (3) Arenisca Pedro Nicolás (Fig. 3). The next description of the members has been taken from Gorustovich et al. (2013). The 74 m-thick Caliza Amblayo Member is composed of a sequence of dark mudstones, yellowish wackestones–packstones and calcareous sandstones. The next member above is the Complejo Don Otto Member, with 67 m of thickness, and composed of three sections. The first section is the "mudstones section", it consists of 9 m in thickness of grey to greenish mudstones and interbedded sandstones lenses. The second one is the "red section" that is composed of calcarenites and clastic reddish sandstones, and depending on the position in the basin, it displays a maximum thickness of 31 m or a minimum of 1 m. The Complejo Don Otto third section, crowning the member, is the "green section" which presents 27 m in thickness. This member is composed of grey calcareous sandstones and interbedded calcareous siltstones, sandstones and mudstones.

In the Valle del Tonco, the last unit of the Yacoraite Formation is the Arenisca Pedro Nicolás Member. It

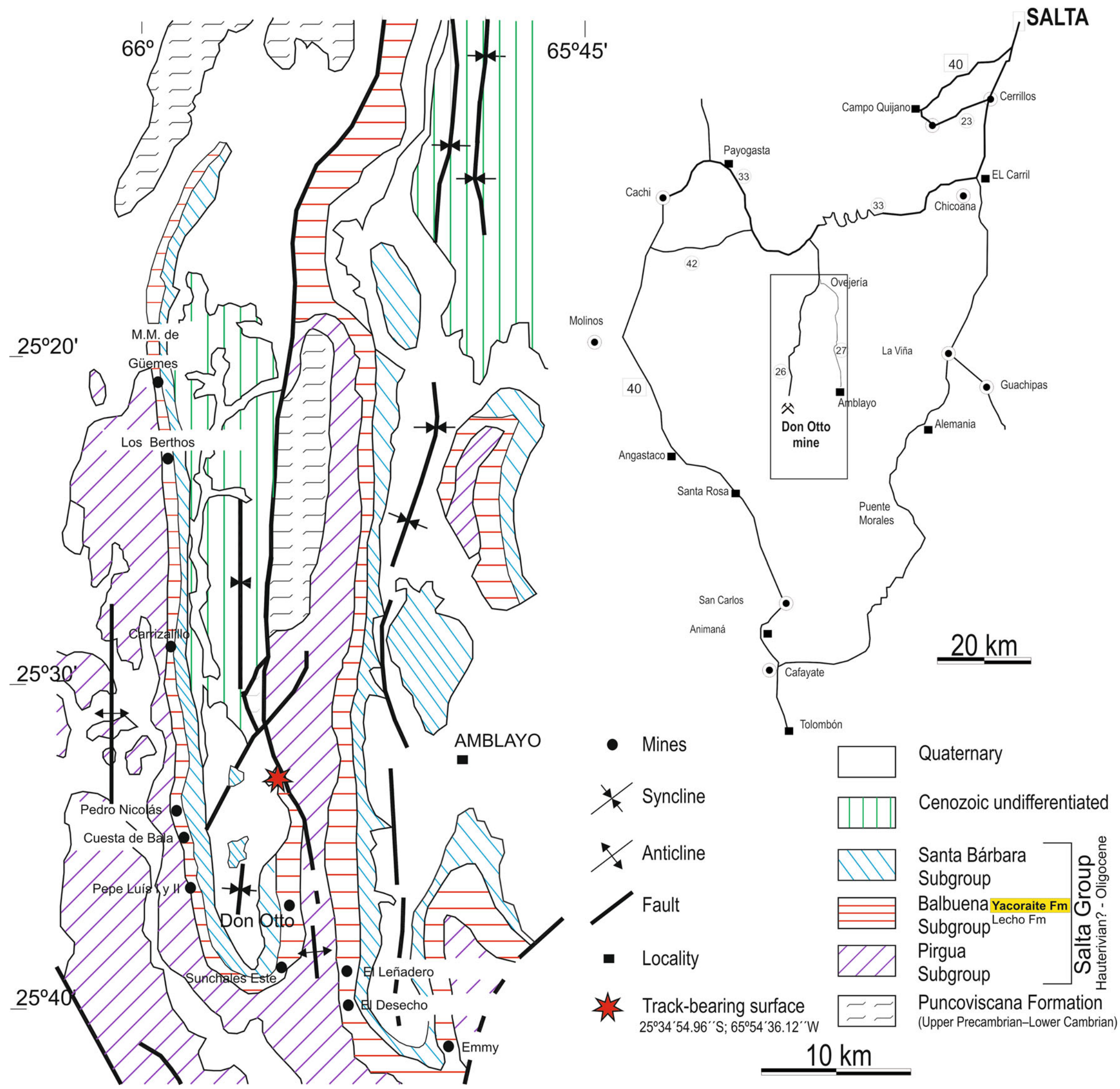


Fig. 2 Geological setting, stratigraphy and location of the Valle del Tonco ichnological site. After Gorustovich et al. (2013)

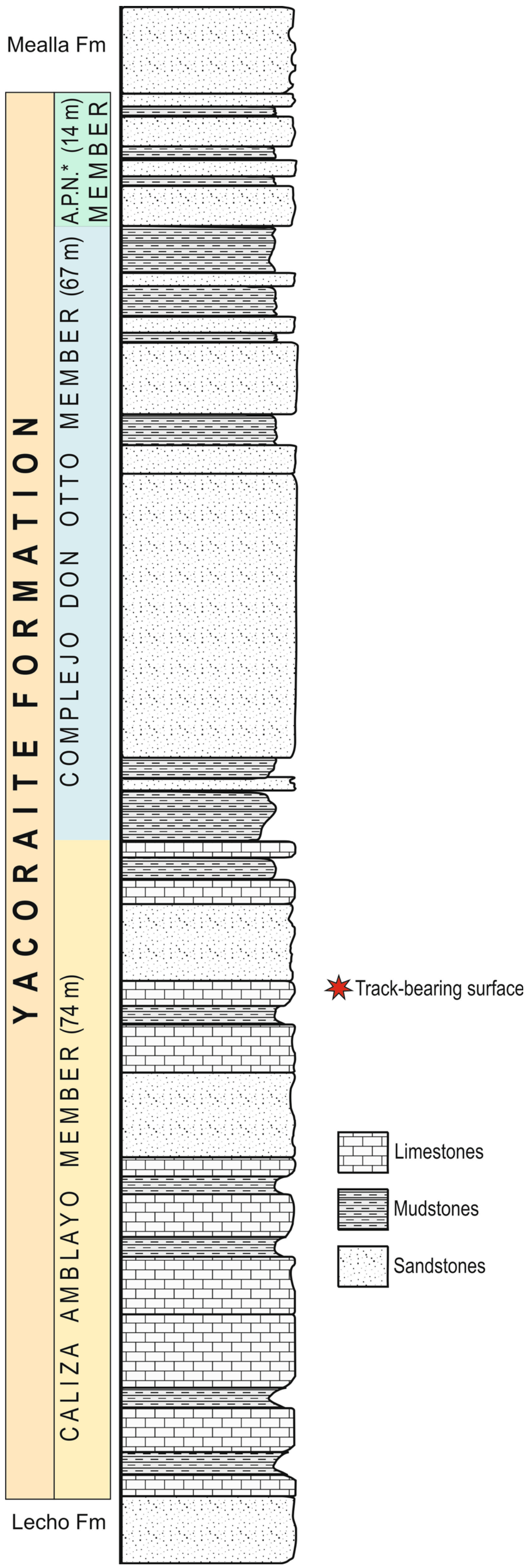
consists of 14 m of white calcareous sandstones interbedded with red siltstones and mudstones.

2.3 Track-bearing surface

The trampled surface studied here is located at the Quebrada de El Candado (25°34′54.96″S; 65°54′36.12″W, Fig. 2). The track-bearing surface belongs to the upper third of the Caliza Amblayo Member, around of 15 m below the top (Fig. 3). The overall sedimentary setting of the Caliza Amblayo Member is indicative of a shallowing upward cyclicity. In the lower third, the stacking pattern of the member display dominance of shales and wackestones–packstones, frequently in heterolithic successions. Along the transition to the middle part of the member section is observed a shallowing pattern, with progressive dominance of coarser carbonates (wackestones to grainstones and oolitic bars), with thicker strata of fine to medium calcareous sandstones. This is suggesting a progressive shift to inland facies. The upper third is composed of heterolitic successions of wackestones and shales, which is indicative of a return to the intertidal activity in fair weather conditions.

3 Materials and methods

The track-bearing surface is a large, subtriangular-sized bedding plane of about 170 m^2. The surface is part of an inverted section (Fig. 4a), which implies that studied tracks are preserved as convex hyporelief. The tracksite shows one sauropod trackway and hundreds of dinosaur tracks in wackestones–packstones facies (Fig. 4b), which have been briefly described previously (Cónsole-Gonella et al. 2015;



◀**Fig. 3** Integrated stratigraphic log of the Valle del Tonco ichnological site (after Alonso and Marquillas 1986; Gorustovich et al. 2013). A.P.N.* is Arenisca Pedro Nicolás

de Valais et al. 2016). Most of the tracks do not have enough morphological details to be related to a particular taxon or ichnotaxon, although some of them have been mentioned as ornithischian tracks (Cónsole-Gonella et al. 2015). As previously commented, in this contribution only the sauropod trackway will be studied in detail.

The measurements and nomenclature used in this study are mainly based on the criteria of Leonardi (1987), Romano et al. (2007) and Marty (2008). The measurements were taken as indicated in Fig. 4c; they are: length (L) and width (W) of pes (p) and manus (m) trackspace angulation (ANG), manus–pes distance (Dm-p), and width of the angulation pattern (WAP). The heteropody was calculated with the heteropody index (H) using the formula by González Riga and Calvo (2009): $H = [(ML \times MW)/(FL \times FW] \times 100$. In addition, to quantify the trackway gauge, the pes trackway ratio (PTR) was calculated as $PTR = (FW/eTW) \times 100$ (Romano et al. 2007).

The photogrammetric models (Falkingham 2012; Mallison and Wings 2014) have been obtained using Agisoft PhotoScanTM (version 0.8.5.1423) software (Grupo Aragosaurus, Universidad de Zaragoza License), with the aim of studying the track morphology through depth maps and contour lines. This method provides for an accurate study of the print depths, which are not easily discernible using traditional methods (mainly because the tracks have eroded surfaces and there are other deformations in the outcrop). Photogrammetric models were also imported into MeshlabTM http://meshlab.sourceforge.net/) for scaling and ParaviewTM (http://www.paraview.org/) to generate false-color maps.

4 Results

4.1 Preservation and condition of the Valle del Tonco tracksite

The studied surface has the casts of hundreds of dinosaur tracks, preserved as convex hyporelief with varied depths (see Fig. 4). The sauropod trackway protrudes far more than the rest, perhaps due to the body weight of the trackmaker, to the conditions of the substrate, or a combination of both. Likewise, there are different generations of tracks in this surface. The trackmakers would have deformed the substrate at different times generating trampled surfaces with different depth and preservation degree. Because the surface is completely trampled, it displays a

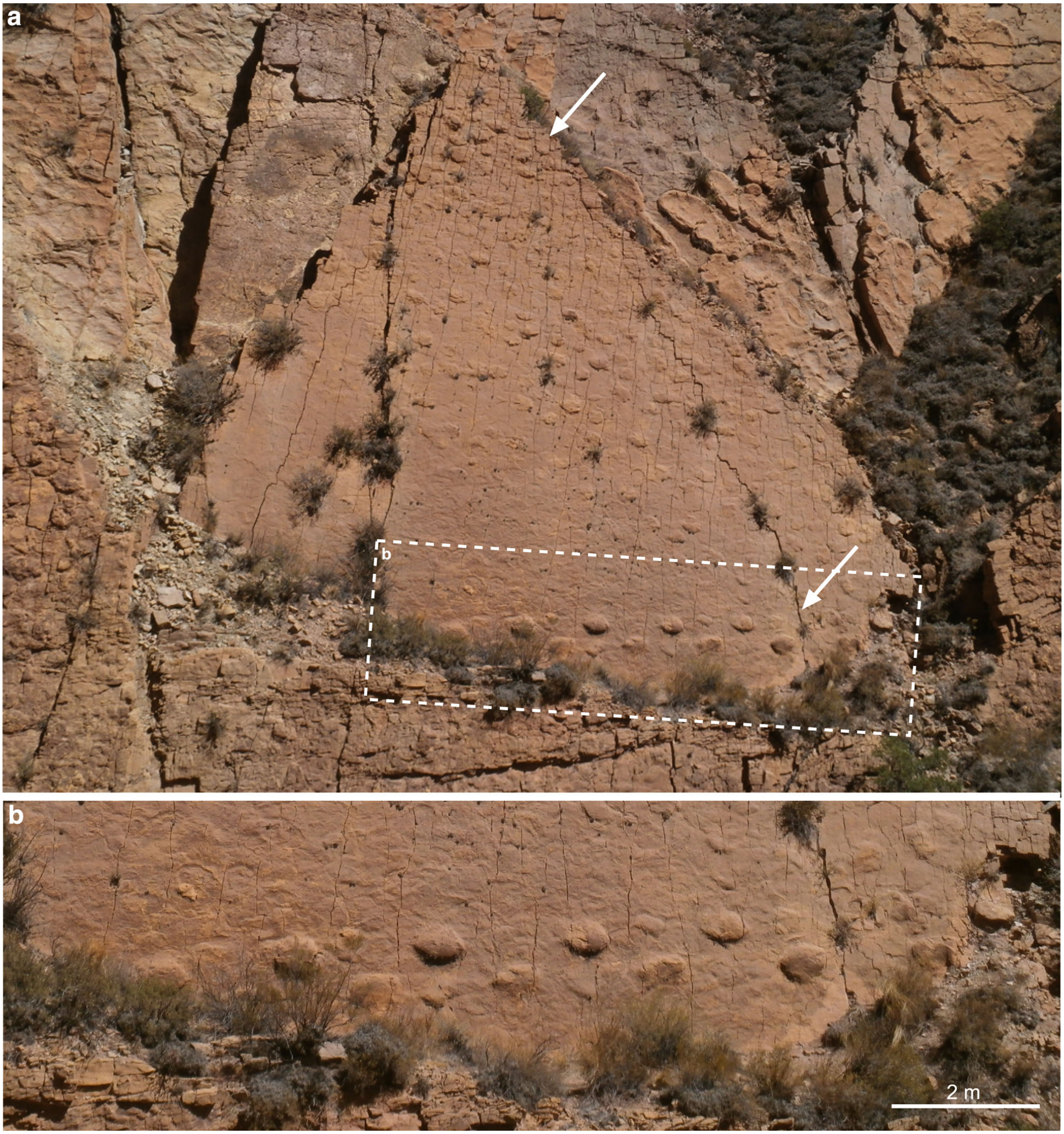


Fig. 4 Valle del Tonco ichnological site: **a** general view of the trampled surface; **b** detailed view of the sauropod trackway. White arrows indicate the sectors with deepest tracks

high track density (high dinoturbation index, sensu Lockley and Conrad 1989), so, causing the tracks to be moderately- to poorly-preserved.

Some of the sauropod pes and manus tracks are over-printing preexisting tracks (1m, 3m, 3p, 5p, 7p, 9p and 12m; Fig. 5a, b), thus the track morphology have been distorted. Nevertheless, in general terms, the outlines are well marked and it is possible to describe the track shapes. Therefore, we consider that they are casts of true tracks or shallow undertracks (sensu Piñuela et al. 2012).

Moreover, the trackway—and the rest of the imprints—is preserved in a very inclined stratum where the rainwater is drained eroding the highest part of the track and keeping the lowest one (i.e., weathered track, sensu Marty et al.

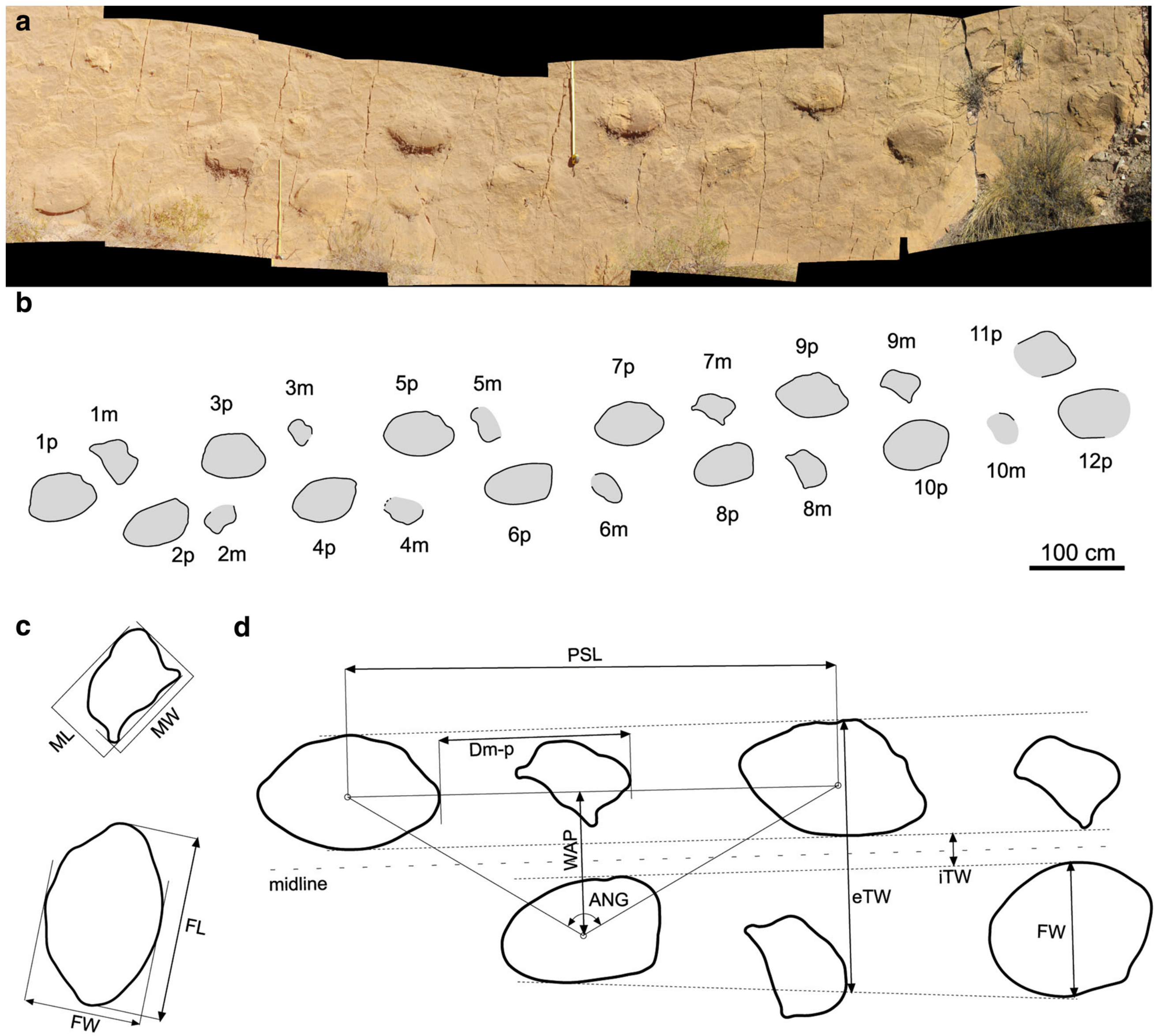


Fig. 5 Valle del Tonco sauropod trackway: **a** panoramic view; **b** interpretative scheme; **c** measurements. *FL* Pes track length, *FW* pes track width, *ML* manus track length, *MW* manus track width, *SL* stride length, *ANG* pace angulation, *Dm-p* manus–pes distance, *WAP* width of the angulation pattern, *iTW* inner trackway width, *eTW* outer trackway width

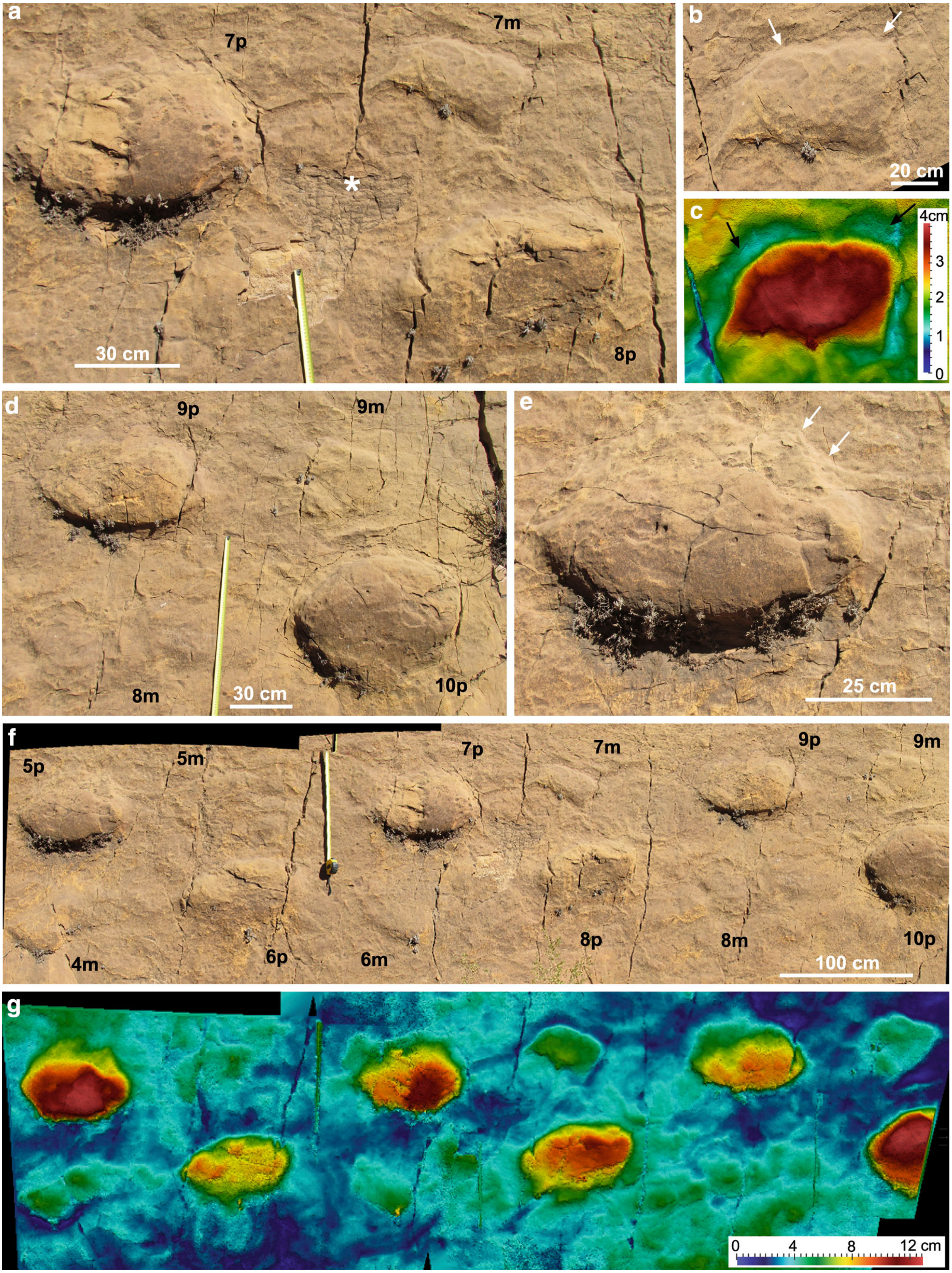
2016). This feature is well represented in the 3D model (Fig. 6g).

Around the sauropod tracks, the mold of slight displacement rims are preserved (Fig. 6c). On the surface (Fig. 6a), there are structures resembling "mat chips" (sensu Gerdes 2007). In this context, these structures suggest the stabilization of substrate that allowed tracks preservation, being adhesive after the downside pressure by the sauropod (e.g., Carvalho et al. 2013). Mat chip structures are frequent in peritidal lakes, lagoons and their adjacent flats, with subaqueous accumulation areas (Gerdes 2007).

4.2 Description of the Valle del Tonco trackway

The specimen includes a trackway consisting of twelve manus–pes set imprints preserved as convex hyporelief (or positive relief as natural casts), produced by a quadrupedal trackmaker (Figs. 5a, b, 6). The measurements are tabulated in Table 1.

The pes tracks have subtriangular posterior edge, a general rhomboidal shape and lack of lateral notch. They are located posteriorly with respect to the manus tracks, with the major axis almost parallel to the trackway midline. The pes prints are longer than wide (averages of length and width: 67 and 42 cm, respectively). Although not clearly



a
7p
7m
*
30 cm
8p
b
20 cm
c
4cm
3
2
1
0
d
9p
9m
8m
30 cm
10p
e
25 cm
f
5p
5m
7p
7m
9p
9m
4m
6p
6m
8p
8m
10p
100 cm
g
0
4
8
12 cm

◀**Fig. 6** Valle del Tonco sauropod tracks: **a** picture of 7p, 7m and 8p tracks; **b** picture and **c** false-color depth map of the photogrammetric model of 7m track; **d** picture of 8m, 9p, 9m and 10p tracks; **e** picture of 5p track; **f** picture and **g** false-color depth map of the photogrammetric model of 4m, 5p, 5m, 6p, 6m, 7p, 7m, 8p, 8m, 9p, 9m, and 10p tracks. White arrows indicate claw-digit impressions, black arrows displacement rim cast, and asterisk mat chips

Table 1 Measurements of Valle del Tonco sauropod trackway

#	L	W	H	PSL	ANG	Dm-p	WAP	PTR
1m	–	–	–	–	–	–	–	–
1p	69	44	–	–	120	–	–	–
2m	16	29	20	–	–	–	–	–
2p	66	35	–	190	126	47	52	45
3m	16	23	14					
3p	59	43	–	184	121	51	66	42
4m	–	–	–	–	–	–	–	–
4p	69	44	–	193	121	–	57	42
5m	–	–	–	–	–	–	–	–
5p	67	43	–	198	125	–	61	42
6m	20	29	23	–	–	–	–	–
6p	65	38	–	211	125	70	55	40
7m	25	38	32	–	–	–	–	–
7p	69	42	–	204	118	72	52	47
8m	28	38	39	–	–	–	–	–
8p	66	41	–	201	121	75	60	42
9m	22	35	27	–	–	–	–	–
9p	67	42	–	208	–	79	67	41
10m	–	–	–	–	–	–	–	–
10p	71	47	–	199	–	–	71	41
11m	–	–	–	–	–	–	–	–
11p	69	45	–	199	–	–	76	38
12m	–	–	–	–	–	–	–	–
12p	–	44	–	–	–	–	–	–
Mean	21/67	32/42	26	198	122	66	61	42

All parameters are given and compared in cm, except ANG in degrees and H and PTR and in %

L track length, *W* track width, *H* heteropody index, *SL* stride length, *ANG* pace angulation, *Dm-p* manus–pes distance, *WAP* width of the angulation pattern, *PTR* pes trackway ratio

marked, in some tracks the digit imprints are laterally located (Fig. 6e).

The manus tracks have few clear morphological details, display about a half of the size of the pes tracks (averages of length and width: 21 and 32 cm, respectively) and are subrounded to rectangular with at least two short, posteriorly oriented digit imprints, although no clear pollex imprint is present (Fig. 6b, c). They have the major axis rotated outwards relative to the trackway midline (about 30°). Pes tracks are deeper impressed than manus tracks (see the 3D model of Fig. 6g). The H is high (mean 26%) being the pes track four times bigger than the manus track.

The trackway displays an average of stride length and pace angulation of the pes tracks of 198 cm and 122°, respectively. The average of the inner and outer trackway width is 14 and 105.7 cm. The average manus–pes imprints distance is 66 cm, although the first measurable distance is quite shorter than the last one (47 vs 79 cm). The width of the angulation pattern varies similar to the manus–pes imprints distance. The first datum is 52 cm increasing along the trackway up to in 76 cm the last one (mean 61 cm). The PTR is of 42% and represents a medium-gauge trackway.

5 Discussion

5.1 Ichnotaxonomy

For a long time, sauropod trackways have usually been differentiated into two categories depending on the distant between the pes tracks and the midline of the trackway: narrow-gauge, when the tracks are located close and wide-gauge when they are far (Farlow 1992; Lockley et al. 1994). Ichnotaxonomically, this is translated as the ichnogenera *Brontopodus* Farlow et al., 1989 related to the wide-gauge trackways, and *Parabrontopodus* Lockley et al., 1994 for the narrow-gauge cases. Given that in many cases it could not be possible to assign into a category to a determined trackway, an intermediate category denominated as medium-gauge has been proposed, although it was not related to a particular ichnotaxon (Lockley et al. 1994; Meyer et al. 1994). Others authors have extended the implications of this concept to other aspects, such as pointing out the importance of the substrate properties and ontogeny and behaviour of the trackmaker in the trackway gauge (i.e., Romano et al. 2007; Marty et al. 2010; Castanera et al. 2012; Torcida et al. 2015; Xing et al. 2015a, b). For instance, Castanera et al. (2012) have described differences in the gauge along the same trackway as results of changes of walking direction or variations in the consistency of the substrate. Xing et al. (2015a) proposed that at least some sauropod ichnotaxa do not maintain a constant gauge during their ontogeny, with narrow-gauge when younger and wide-gauge when older. Thus, the manus and pes track shape has been suggested as the most important ichnotaxobase in sauropod or sauropod-like tracks ichnotaxonomy (Wright 2005; Castanera et al. 2016). In this study, this last proposal has been followed.

Breviparopus Dutuit and Ouazzouz, 1980, from the Upper Jurassic of Morocco, presents a pes tracks with four digit impressions located and oriented anteriorly and with a lateral notch. The manus print is symmetrical, crescent-shaped, and without digit imprints. *Parabrontopodus* Lockley et al., 1994, originally created to assign several specimens from the Late Jurassic Morrison Formation from Colorado, USA, has the I, II and III claw traces oriented laterally in the anterolateral sector of the pes track, and lacks a clear lateral notch. It has a pronounced heteropody, with symmetrical, crescent-shaped manus prints, with no digit imprints. The pes tracks belong to *Polyonyx* Santos et al., 2009, from the Middle Jurassic Serra de Aire Formation, from Serra de Aire, West-central of Portugal, lack of lateral notch. They have the I and II claw traces oriented anteriorly, while the III and IV claw traces are laterally oriented. All the claw traces are in the anterior part of the track. The manus prints are asymmetrical, "speech-bubble" shaped (sensu Castanera et al. 2016), with pollex imprint anteromedially directed, and digits II–V imprints with bent arrangement. *Brontopodus* Farlow et al., 1989, which has been originally named to group trackways from the Early Cretaceous of Texas, USA, is characterized by having pes tracks with outwardly directed claw traces at digits I–IV in the anterolateral part of the track and clear lateral notch. The manus imprints are symmetrical, U-shaped and with two digit impressions oriented posteriorly. *Titanopodus* González-Riga and Calvo, 2009, from the Late Campanian–Early Maastrichtian Loncoche Formation from Mendoza province, Argentina, represents pes tracks lacking claw, digit imprints and lateral notch. The manus prints seem to be asymmetrical, crescent-shaped and without digit impressions. The main shape of these manus tracks could be related to extramorphological features. However, the poor preservation of the material and the lack of proper available pictures from the literature (no specimens or artificial cast has been collected), make the comparisons difficult.

Although most of the Valle del Tonco tracks are poorly-preserved, some of them keep detailed morphology, and, for instance, moderate well-preserved claw or digit impression and a clear track outline can be observed (Fig. 6e). In that cases, pes tracks are rhomboidal, lack of lateral notch and the digit-claw traces are laterally located. The better-preserved manus tracks (Fig. 6a–d) are rectangular with at least two short, posteriorly oriented digit imprints, and without a marked pollex impression. The Valle del Tonco tracks present high heteropody, and this feature is unusual among other Cretaceous sauropod trackways (Lockley et al. 1994).

The combination of the displayed ichnotaxobases by the Valle del Tonco tracks does not allow it to link them to any ichnogenerical diagnosis. The pes tracks have a general morphology, with the lateral digit imprints and lacking a lateral notch, different from the rest of the record. However, it is interesting to note comparisons with other ichnotaxa. Respecting the manus tracks, they are morphologically variable, being the more complete subrounded to rectangular and resemble a partial *Brontopodus* manus print which lacks the lateral digit imprints.

5.2 Uppermost Cretaceous sauropod ichnodiversity

The abundant presence of sauropod dinosaur bones in the uppermost Cretaceous (Campanian–Maastrichtian) worldwide rocks is well known and pertains to the titanosaurs at this time (e.g., García et al. 2015; Gónzalez Riga et al. 2016 and references herein). Nevertheless, the ichnological record of this group of dinosaurs is very scarce in this temporal interval, as can be noted in their worldwide distribution (Fig. 7; Table 2). From the Campanian–Maastrichtian Yucheon Group (Yeosu Islands area, South Korea), three slightly wide-gauge sauropod trackways have been described (Paik et al. 2006; Lockley et al. 2012). According to Lockley et al. (2012), the pes tracks are tetradactyl with at least three claw traces oriented laterally along the antero-lateral margin of the track and they lack a lateral notch, while the manus tracks are rectangular to U-shaped without digit impressions. Unfortunately, there are not enough good pictures showing details of the Korean tracks. *Titanopodus mendozensis* González Riga and Calvo 2009, from the upper Campanian–lower Maastrichtian Loncoche Formation, Mendoza province, Argentina, was defined based on two trackways which, as has been mentioned above, evidently display extramorphological features.

Three tracksites with sauropod trackways have been described in Campanian–Maastrichtian levels from Bolivia (Leonardi 1984, 1994; Meyer et al. 2001; Lockley et al. 2002; Apesteguía et al. 2007). The Toro Toro tracksite (Toro Toro Formation, Campanian), at north of the Potosí Department, presents one adult and two young, sauropod trackways, in a probably gregarious disposition (Leonardi 1984, 1994; Lockley et al. 2002). These tracks have conspicuous mud rims that affect their preservation, and consequently their morphology (see Lockley et al. 2002). Some pes tracks show at least three claw impressions anteriorly directed and lateral notches, and the manus tracks are characterized by three sharper, central claw traces, but they have no uniform shape (such as U-shaped, rectangular, crescent-shaped). The trackways are wide-gauge, with a high heteropody including manus tracks as long as those of the pes (manus–pes area ratio of 1:1). The Humaca tracksite (Chaunaca Formation, Campanian), situated about 60 WSW of Sucre city, Potosí Department, has at least eleven parallel sauropod trackways (Lockley et al. 2002). The well-preserved pes tracks shows the I, II and III claw traces in the anterior margin of the track and have a clear lateral notch. The manus tracks are laterally

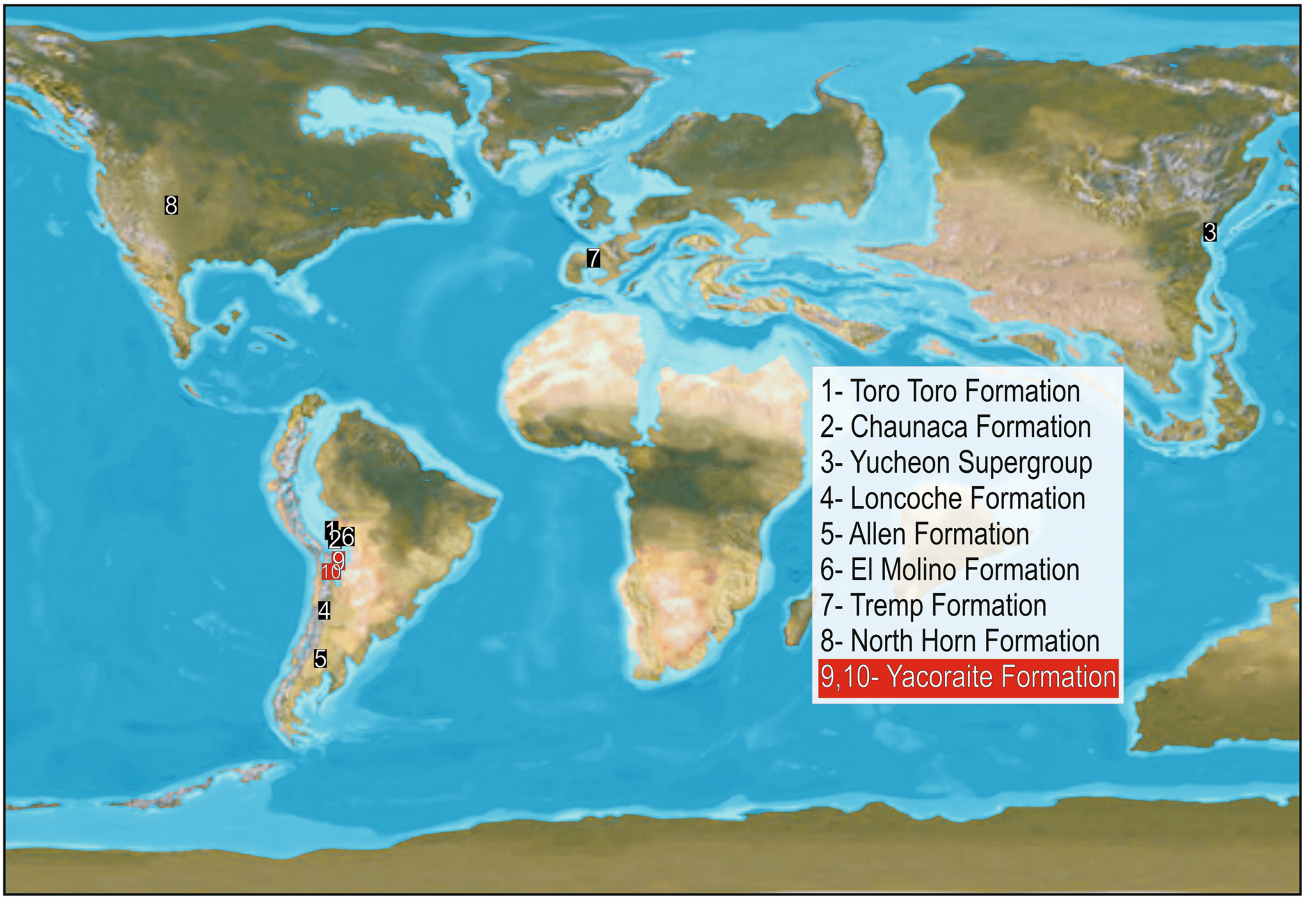


Fig. 7 Palaeobiogeographic distribution of Campanian–Maastrichtian sauropod tracks record. More information in Table 2. Palaeogeographic map modified from reconstructions by Ron Blakey, NAU Geology (http://jan.ucc.nau.edu/~rcb7/065Marect.jpg)

symmetrical, rectangular to U-shaped, and some of them show five rounded callosities or blunt claw impressions. The trackways are wide-gauge and have low heteropody (between 1:2 and 1:3). At the Cal Orck'o tracksite, beside Sucre city, several sauropod trackways have been recorded in a unique level—belonging to a quarry producing cement by FANCESA company—from the Maastrichtian El Molino Formation (see Meyer et al. 2001; Lockley et al. 2002; Apesteguía et al. 2007). Nowadays, the sector of the surface bearing the two most famous of these trackways, which were disposed in a parallel way, has fallen down and it is completely destroyed. The shape of the unaffected tracks is very variable due to the mud physical properties (see Lockley et al. 2002; de Valais, *pers. obs.*). Pes tracks lack of digit impressions and clear lateral notch. The manus tracks are U-shaped, rectangular or semicircular and have no evidence of digit impressions. The trackways are moderate wide-gauge and have low heteropody (manus–pes area ratio of 1:2).

At the Fumanya locality, in the Pyrenees, Spain, about 51 sauropod trackways from the Maastrichtian Tremp Formation have been studied (Vila et al. 2005, 2008, 2013). The better-preserved pes tracks present four claw traces oriented laterally in the anterolateral surface of the track and lack of clear lateral notch. Manus tracks are symmetrical, subrectangular to U-shaped, without claw traces. Vila et al. (2008) pointed out that the trackways are wide-gauge with a heteropody of 1:3.

Several poorly preserved tracks, some of them comprised of trackways, and at least one manus–pes set on a trampled, deteriorated surface, have been recorded from the Maastrichtian Yacoraite Formation, Maimará locality, Jujuy province, Argentina (Cónsole-Gonella et al. 2017). Cónsole-Gonella et al. (2017) mentioned that the footprints have no digit impressions neither lateral notch, manus tracks are semicircular in shape without other anatomical impression, and the heteropody is approximately 1:2; they have also suggested that the trackway is moderate wide-gauge. In addition, other sauropod tracks have been published from the Maastrichtian North Horn Formation of Utah, USA (Difley and Ekdale 2002), or mentioned from the Paso Córdoba locality, Río Negro province, from the Campanian–Maastrichtian Allen Formation of Argentina

Table 2 Geographical and temporal distribution of Campanian–Maastrichtian sauropod tracks

Track records	Lithostratigraphic unit	Age	Locality	References
Sauropod tracks	Toro Toro Formation	Campanian	Toro Toro (Bolivia)	Leonardi (1994), Meyer et al. (2001), Lockley et al. (2002)
Sauropod tracks	Chaunaca Formation	Campanian	Humaca (Bolivia)	Meyer et al. (2001), Lockley et al. (2002)
Sauropod tracks	Yucheon Supergroup	Campanian–Maastrichtian	Yeosu (Korea)	Paik et al. (2006), Lockley et al. (2012)
Titanopodus mendocensis	Loncoche Formation	Late Campanian–Early Maastrichtian	Mendoza (Argentina)	González Riga and Calvo (2009)
Sauropod tracks	Allen Formation	Late Campanian–Early Maastrichtian	Río Negro (Argentina)	Calvo and Ortíz (2011), Ortíz and Calvo (2016)
Titanosaurid tracks	El Molino Formation	Maastrichtian	Cal Orck'o (Bolivia)	Meyer et al. (2001), Lockley et al. (2002), Apesteguía et al. (2007)
Cf. *Brontopodus*	Tremp Formation	Maastrichtian	Pyrenees (Spain)	Schulp et al. (1999), Vila et al. (2005, 2008, 2013)
Sauropod? Tracks	North Horn Formation	Maastrichtian	Utah (USA)	Difley and Ekdale (2002)
Titanosaur tracks	Yacoraite Formation	Maastrichtian–Danian	Jujuy (Argentina)	Cónsole-Gonella et al. (2012, 2013, 2017)
Sauropod tracks	Yacoraite Formation	Maastrichtian–Danian	Salta (Argentina)	Cónsole-Gonella et al. (2015), In this work

(Calvo and Ortíz 2011). Nevertheless, there are no suitable figures or detailed descriptions so no comparisons can be done with confidence.

Taking into account the above descriptions of the Campanian–Maastrichtian sauropod tracks, almost all the records are poorly-preserved. Anyway, based on the best-preserved pes tracks (manus tracks are morphologically more variable), two different general shapes are considered (Fig. 8): (1) the Humaca shape, represented by the Campanian Humaca pes tracks, with claw traces located anterolaterally and a clear lateral notch; and (2) the Fumanya shape, represented by the Maastrichtian Fumanya pes tracks, with claw traces laterally oriented and lacking a lateral notch.

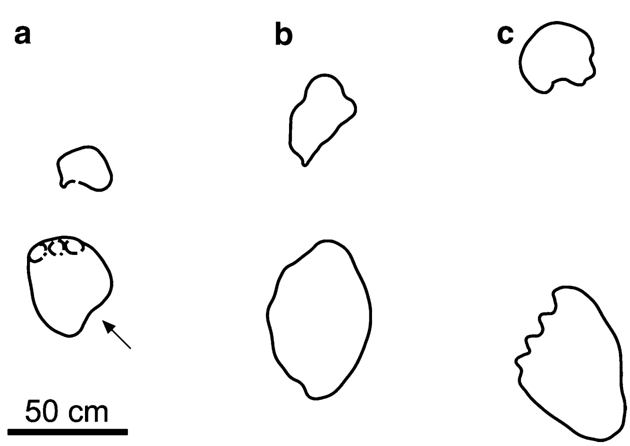


Fig. 8 Ichnodiversity of Campanian–Maastrichtian sauropod tracks: **a** Humaca redrawn from Lockley et al. (2002), **b** Valle del Tonco, and **c** Fumanya manus and pes tracks redrawn from Castanera et al. (2016). Black arrow indicates the lateral notch

Although, geographically it would be expected that the Maastrichtian Argentinian Valle del Tonco specimens were similar to the Bolivian Humaca ones, the Valle del Tonco pes tracks share some features (i.e., claw traces laterally oriented and without a lateral notch) with those belonging to the Maastrichtian Spanish Fumanya shape. All other known Campanian–Maastrichtian sauropod tracks are poorly preserved and it is too complicated to relate them with any of both morphological groups.

The lattermost Cretaceous sauropod tracks are generally assigned to titanosaur sauropods taking into account their ichnological features (trackway gauge) and the biostratigraphical context (they are the only group of sauropods recorded for this time) (Vila et al. 2005; González Riga and Calvo 2009). The Campanian Humaca pes tracks are similar to the Early Cretaceous (Aptian–Albian) *Brontopodus* ichnotaxon. Some authors related this ichnotaxon to titanosaurs (i.e., Salgado and Calvo 1997; Santos et al. 2009) or more broadly with titanosauriformes (i.e., Wilson and Carrano 1999; Wilson 2005). This fact suggests that the pes track shape is very similar within this dinosaur clade of trackmakers (at least from the "mid" Cretaceous to Campanian), and supports the idea that the sauropod feet are in essence, morphologically conservative (Farlow 1992; Castanera et al. 2016). On the other hand, the Fumanya tracks, which have been related with titanosaurs as well (see Vila et al. 2013), present a very distinctive pes track shape. Thereby, in the uppermost Cretaceous rocks there would be at least two different feet morphology within the clade Titanosauria.

6 Conclusions

Herein, a new sauropod dinosaur trackway is analyzed from the Yacoraite Formation (Masstrichtian–Danian), in the Quebrada de El Candado, Valle del Tonco tracksite, northwestern of Argentina. The trackway contains twelve manus–pes set imprints preserved as convex hyporelief (natural casts) in a surface that is part of an inverted section. The sauropod tracks are partially eroded but some of them have well defined contour line. The best preserved pes tracks are longer than wide, rhomboidal, whit a subtriangular posterior edge, lacking lateral notch. When are preserved, the digit-claw traces are laterally located. The manus tracks are subrounded to rectangular with two short, posteriorly oriented digit imprints, and without a marked pollex impression. Based on the ichnotaxobases, the Valle del Tonco sauropod tracks are different enough from the already defined sauropod ichnotaxa, but, taking into account that their shape could be affected by the preservation and/or weathering, it is not possible to confirm it with confidence.

The sauropod ichnological record, generally related to titanosaur trackmakers, is scarce in the Campanian–Maastrichtian worldwide rocks. Among this record, two different pes track shape are identified: the Humaca shape, for the Campanian Chaunaca Formation tracks, from Bolivia; and the Fumanya shape, for the Maastrichtian Tremp Formation tracks, from Spain. The Valle del Tonco tracks are morphologically closed to Fumanya shape. The Humaca shape is similar to the Aptian–Albian *Brontopodus* ichnotaxon that suggests conservative titanosaur pes track morphology from the lapse "mid" Cretaceous to at least the Campanian. The presence of Fumanya-shaped-tracks in rocks of similar age to those from Humaca allows us to suggest that at least two different titanosaur pes tracks shapes and hence two feet morphologies are present in the uppermost Cretaceous rocks. The relationships between the Campanian–Maastrichtian titanosaur autopods and tracks and their evolutionary context is suggestive to further work.

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